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TOTAL ELECTRON CONTENT FORECASTING AT AFGWC.(U)
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TOTAL ELECTRON FORECASTING AT AFGWC

BY

CAPT JAMES A. MANLEY

FEBRUARY 1981

UNITED STATES AIR FORCE
AIR WEATHER SERVICE (MAC)
AIR FORCE GLOBAL WEATHER CENTRAL
OFFUTT AFB NE 68113

17 JUN 1981

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BY

CAPT JAMES A. MANLEY

FEBRUARY 1981

UNITED STATES AIR FORCE
AIR WEATHER SERVICE (MAC)
AIR FORCE GLOBAL WEATHER CENTRAL
OFFUTT AFB NE 68113

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INTRODUCTION

The purpose of this paper is to provide a qualitative assessment of total electron content (TEC) forecasting at the Air Force Global Weather Central (AFGWC). It is based on five years of forecasting experience encompassing the extremes of TEC variation between solar minimum and solar maximum. TEC products are generally of two types: an area forecast or a point forecast. Area forecasts are for geographical areas on the order of ten degrees of latitude and longitude or larger. In general, the desired goal is to predict or specify TEC within $\pm$ 5 X 10^{16} electrons/m^2. Throughout this paper the various aspects of the prediction and specification process will be examined. A detailed discussion of TEC modeling techniques is beyond the scope of this paper. Instead the difficulties and subjectivity of the forecast process will be emphasized.

OBSERVATIONAL DATA

The available data set includes hourly TEC observations from 12 polarimeter sites that monitor VHF beacons on geosychronous satellites. Seven of these locations are 24 hour per day reporting sites. The remaining sites operate during normal duty hours and report the remaining observations in a daily summary. This "network" of TEC observing sites is complemented by ground based vertical incidence (V.I.) sounders. Six V.I. sounder sites transmit data on a 24 hour per day basis. Summary data are received between 12-72 hours after the observation times from an additional 25-30 stations.

TEC observations have proven to be the key input parameter to the forecast. The TEC observations have a number of problems, foremost of which is the lack of sufficient observing sites. For area forecasts one would ideally like to have the forecast area boxed in by observing sites. For areas that cover a large latitudinal variation, a chain of stations along the same meridian is desirable. A good example of this is the chain of polarimeter sites along the North American east coast consisting of: Goose Bay, Labrador; Sagamore Hill, Massachusetts; Patrick AFB, Florida; and Ramey AFB, Puerto Rico. This chain can effectively monitor the high and middle latitude ionosphere and lacks only an equatorial station. Such chains of observing sites near the same meridian record the ionosphere near the same local time and greatly aid the forecaster in identifying synoptic patterns that exist in a local time frame. Three or four such meridional chains are needed to monitor TEC on a worldwide basis. For forecasts in areas of high ionospheric variability such as the auroral zone or equatorial region, additional TEC sites are needed as well as more frequent observations. Observations from these areas should routinely be transmitted every fifteen minutes. During disturbed conditions, fifteen minute observations should also be received from middle latitude stations.

Data receipt and reliability are other problems the forecaster has to contend with. Overseas locations often experience communication outages or delays. This, combined with the small number of observing sites, can lead to a very sparse data base at times. The quality of the observations are occasionally suspect or in error, because the observer personnel lack both the knowledge of ionospheric variabilities and training needed to interpret the data. This is particularly true during disturbed ionospheric conditions when rapid variations occur that make TEC measurements difficult for the best of observers. The result of these erroneous observations is that TEC observations from a given station may be in error by 5-10 X 10^{16} electrons/m^2 for periods ranging from several hours to several days. Such values exceed the desired forecast goals, and the erroneous data is difficult to identify due to the lack of corroborating ionospheric data.

Several of the polarimeter sites are completely automated. While this has the advantage of 24 hour per day observations, the software occasionally has difficulties in keeping track of the TEC values during disturbances and the sunrise transition period. With unmanned sites, the correction of such problems is even more difficult. An additional problem, which is becoming increasingly more critical, is the declining availability of VHF beacons on geosychronous satellites. Not only does this limit the geographic extent of the observing network, but the operation and maintenance of the satellites and their beacons are not under the control of the TEC monitoring network. Add to this the lack of standardized observing equipment and centralized control, and the problems associated with the operation and maintenance become more complex. From the forecaster's standpoint, this results in an excessive amount of time spent in data acquisition and validation.

FORECAST MODELS

There are several approaches to input data into the AFGWC 4-D ionospheric model. TEC data can be used as the primary input parameters, or it can be combined with foF2 data to produce TEC specification fields. Another option is to use only foF2 data. A fourth option is to use the Institute of Telecommunications Service (ITS) data fields. It should be noted that all of the ionospheric models in use are specification models that have no physical dynamics built into them. Background information concerning ionospheric modeling efforts at AFGWC is contained in a paper by Tascione et al, 1979 (see references). The TEC forecast products are a result of forecaster modification of the model or model output based on experience.

On a given day any one or more of the various input parameters may produce the best TEC specification field. Over the long term; however, the option using foF2 and TEC data produces the best TEC specification. This method uses considerable computer time and produces only a slightly better TEC field than the use of TEC alone as an input parameter. The use of foF2 observations produces good TEC specification on some days but lacks the consistency for use on a day-to-day basis. The ITS fields also suffer from a similar lack of consistency.

TEC fields produced from the ITS model are not viable for routine daily forecasts. Predictions/specifications from the ITS model are often mistaken for climatology. There is no TEC climatology except for the data currently being collected. The basic input for the ITS model is a sunspot number (SSN). The best available sunspot number for ionospheric purposes is the effective sunspot number (SSN_{eff}) produced from actual foF2 observations. Table 1 shows the extreme variation in daily effective sunspot numbers calculated through the month. The variations between low and high daily values within a given month range from 50-60 to over 100. These effective sunspot numbers are the best fit of an ITS field to the observed foF2 values for a given day. The use of an ITS field specified on other than a daily basis could result in extremely poor TEC fields depending upon the particular ionospheric conditions on a given day.

TABLE I

Daily Effective Sunspot Number

MONTH	LOW	HIGH
Jul 1978	72	142
Aug	60	119
Sep	54	117
Oct	84	137
Nov	84	132
Dec 1978	89	118
Jan 1979	112	140
Feb	142	193
Mar	114	200
Apr	88	200
May	99	181
Jun	107	172
Jul	112	145
Sep	121	140
Oct	122	184
Nov	131	181
Dec 1979	121	177
Jan 1980	124	158
Feb	123	160

To illustrate some of the TEC variations consider the following. For February 1980, a TEC field generated from ITS fields with sunspot numbers of 120, 140, and 175 at a time of 1100Z would produce the following TEC variations.

TABLE 2

ITS TEC (10^{16} electrons/m^2)

LOCATION	SSN:	120	140	175
Athens		48	57	76
Osan		26	32	44
Taiwan		68	81	105

Observed values at 1100Z during Feb 1980 were:

LOCATION	Minimum	Maximum
Athens	35	72
Osan	14	34
Taiwan	51	125

The observed values above are not the extremes associated with large disturbances but typical of daily variations within a given month. If, for example, TEC predictions were issued on a monthly basis using the ITS fields, large differences between predicted and observed TEC values could be expected during undisturbed conditions. Use of monthly predictions also neglects the following:

1. The day-to-day variablity of the equatorial and auroral zone regions is not considered.

2. Quiet day TEC values and patterns are often quite different between the Eastern and Western Hemispheres.

3. Seasonal changes in the ionospheric characteristics can occur at different times then the calendar season change.

During disturbed ionospheric conditions, ITS fields are totally unrepresentative. TEC variations can be extreme. For example, during a storm, values at Osan, Korea can be 30 TEC units (1 TEC unit = 1.0×10^{16} electrons/m^2) below the previous quiet day values. At the same time, TEC values at Athens, Greece can be 30 TEC units above the previous quiet day's value. On one occasion, nighttime values at Palehua, Hawaii jumped nearly 25 TEC units (typical values are 5-8 TEC units) for several hours. TEC values at Taiwan have changed from values of $>$ 150 TEC units on a quiet day to values of $<$ 50 on the following disturbed day.

QUIET DAY TEC FORECASTS

The ionosphere can show remarkable variations even during undisturbed conditions. The quiet day variations sometimes match storm variations. That is, sometimes large increases or decreases are noted for a day or more with no significant geomagnetic disturbances in progress. Generally, the rapid variations often observed during geomagnetic storms are lacking but the magnitude of the TEC change can be comparable. Large gradients of TEC are also apparent in certain areas. For example, on some days Palehua, Hawaii TEC values are similar to middle latitude stations. On other days it resembles an equatorial ionospheric station such as Taiwan. It should also be noted that despite the relatively small geographical separation, daytime TEC values at Taiwan are nearly double those of Osan, Korea. Nighttime values show even greater differences.

The approach to TEC forecasting during quiet conditions is to have the model build a specification field based on persistence or five day mean TEC values. The forecaster has some flexibility in use of the model so that unrepresentative TEC for various stations or days can be excluded from the desired specification field. By monitoring and displaying the TEC data on a routine basis the forecaster attempts to identify synoptic patterns and trends for application to the specification fields produced by the model. The forecaster can then apply the changes necessary to modify the model output or the TEC forecast itself. In the case of TEC forecasts over large areas and/or time periods, the forecaster can make changes by area or local time application of weighting factors. These factors then produce the desired increases or decreases in predicted TEC values.

DISTURBED DAY TEC FORECASTS

During disturbed ionospheric conditions the forecast problem is much more difficult. Not all geomagnetic disturbances produce observed large scale TEC variations. At other times similar geomagnetic disturbances produce completely different TEC responses. There appears to be a marginal correlation between the magnitude of the storm and the magnitude of the TEC variations. The sparsity of data precludes early detection and continual monitoring of the disturbance. Figures 1 through 6 illustrate the type of TFC variation that is possible during a disturbance. The forecast process is hampered by the lack of a dynamic prediction model and essentially no prediction tools for the forecaster. Storm morphology in the research literature, until recently, has concentrated on the middle latitude and is generally based on a single station. As a general rule the forecaster will look for TEC increases (positive phase) of 30 to 50 percent above the quiet day values early in the disturbance followed by a sharp decrease (negative phase) to below quiet day values. The enhancement figure of 30 percent above the quiet day value appears to be a common value for middle latitudes. The timing of positive and negative phases is very difficult. On a global basis, one hemisphere may be in one phase while the other hemisphere experiences the opposite phase. Often the forecast is out of phase with the observed values.

FORECAST VERIFICATION

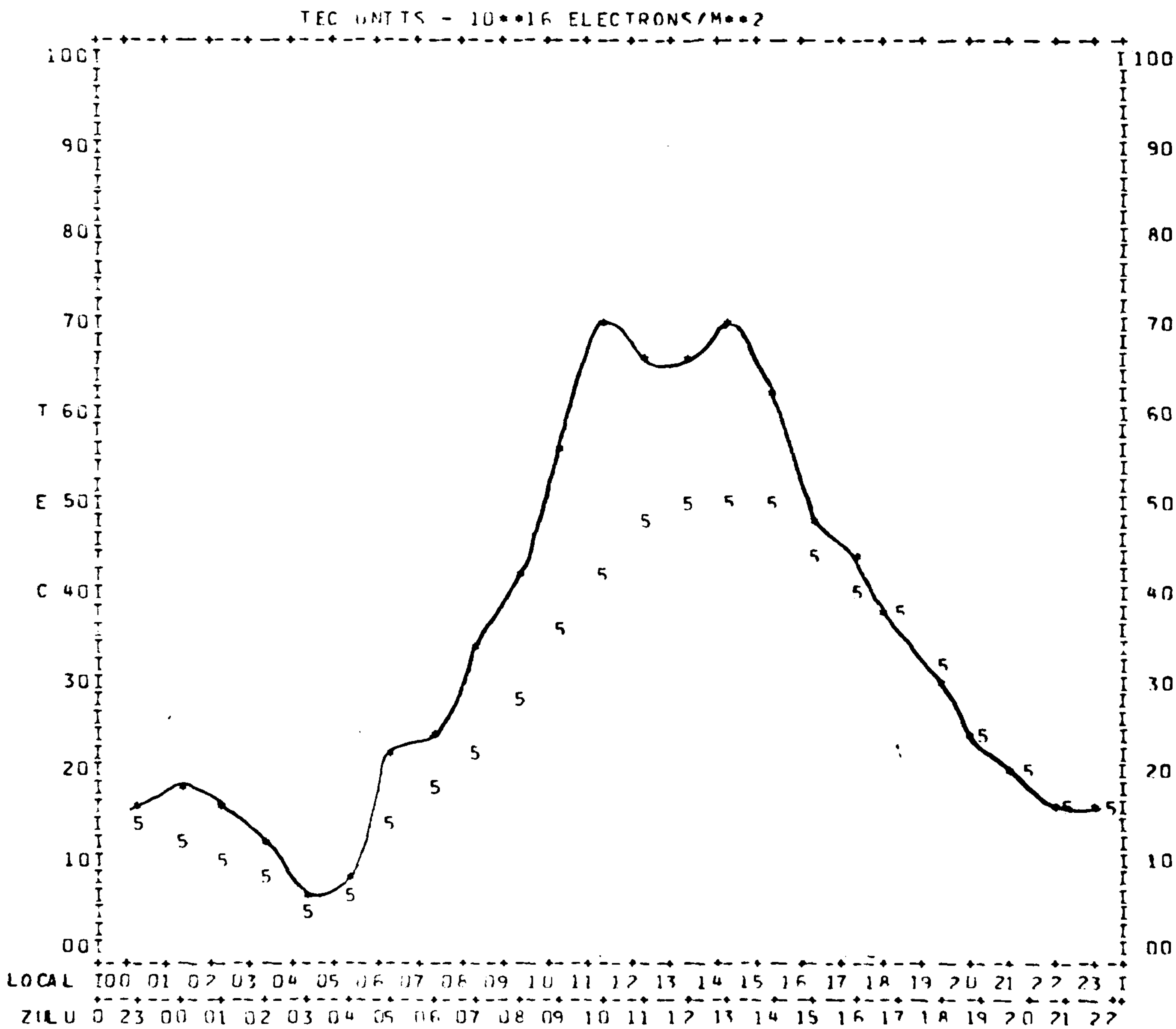
The verification of point forecasts in areas where observational data exists is straightforward and can be done in a variety of ways. In areas where there are no TEC observations, feedback from the user of the TEC forecast is the only mechanism for evaluating the forecast. Since most users are interested in TEC forecasts over an area rather than a single point, the use of observations from a single station is very risky if the area extends very far in either latitude or longitude. Some attempts have been made to use observations from a few stations as verification data representative of a given latitude regime on a worldwide basis. For example, a TEC forecast for the middle of the Pacific Ocean would be verified for the same local time using a middle latitude station on the east coast of the U.S. These schemes neglect the fact that the forecaster modifications are for the forecast area not the area of the verification data. Such efforts are analogous to using Omaha, Nebraska weather observations to verify a weather forecast for Los Angeles, California. Until a high density network of observations is available, the only practical verification scheme is some measure of the forecast's value by the user.

SOLAR CYCLE EFFECTS ON TEC FORECASTING

A few comments concerning the variation of TEC during the solar cycle and its effect on TEC forecasting should be made. Figure 7 illustrates the typical differences of TEC values during solar minimum and maximum conditions. Maximum daily TEC values at the middle latitude during solar minimum are on the order of 15-25 X 10^{16} electrons/m^2 compared to values of 60-70 X 10^{16} electrons/m^2 during solar maximum. Even more extreme variations are exhibited in the equatorial region where peak daily values of 50 X 10^{16} electrons/m^2 during solar minimum changed to values of 150 X 10^{16} electrons/m^2 during solar maximum. Nighttime values of TEC remain relatively stable during the solar cycle with values of 5-10 X 10^{16} electrons/m^2.

STATION ATHENS
DATE(LOCAL) 90425
GEOM. LAT. +28
SATELLITE SIRO
I.P.P. N34 E 20

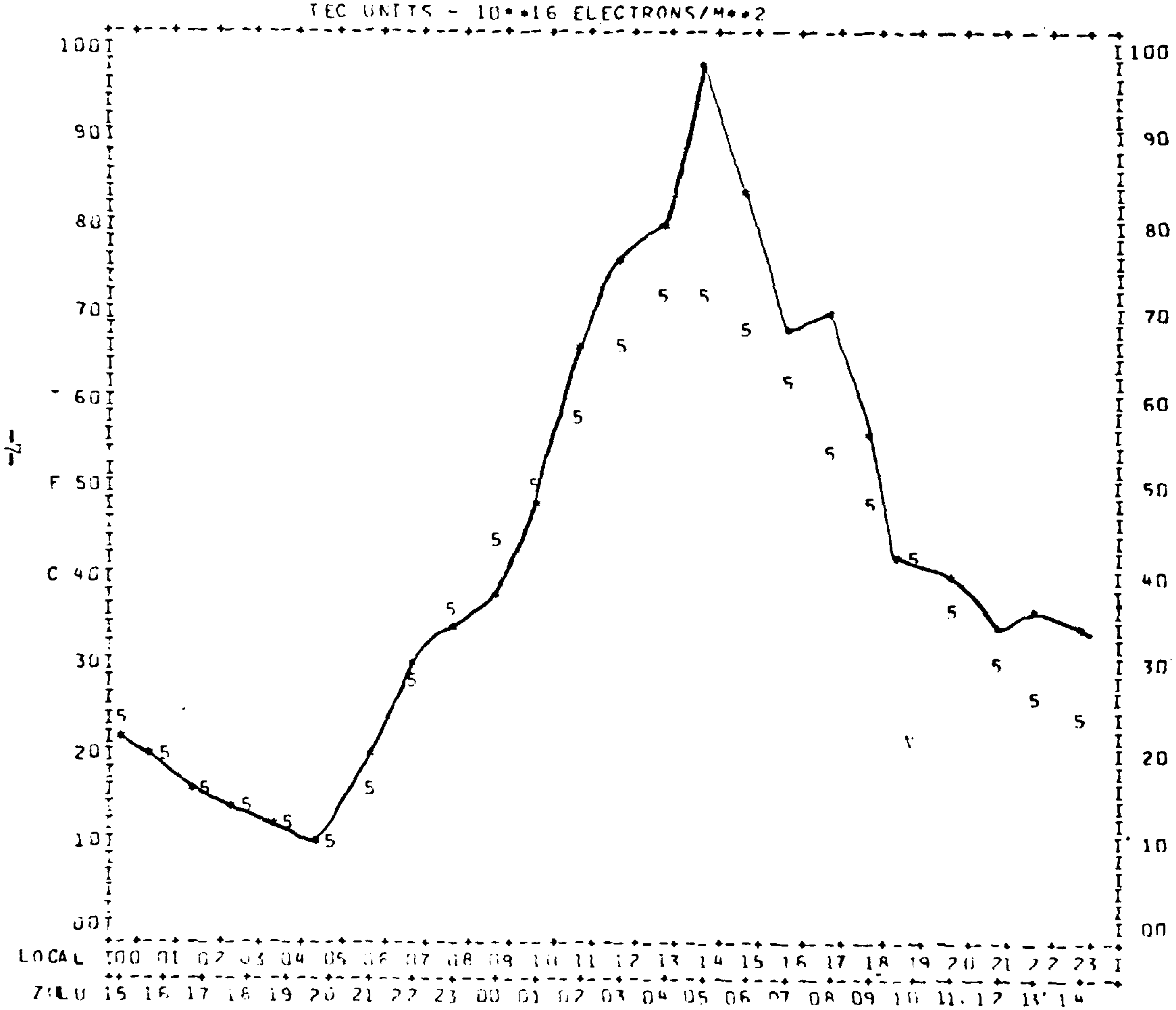
5 = five day mean
* = daily TEC value



TIME(L)	TEC	MEAN
00	16.4	12.8
01	16.8	11.6
02	14.9	10.0
03	11.9	6.5
04	5.3	3.5
05	7.5	5.7
06	22.2	12.8
07	24.3	16.8
08	33.1	22.0
09	42.1	28.3
10	54.8	34.9
11	68.9	40.7
12	64.9	47.0
13	65.9	48.6
14	69.9	48.9
15	61.3	48.6
16	47.5	44.0
17	43.4	39.9
18	37.9	37.3
19	29.0	31.8
20	23.2	24.4
21	18.5	19.1
22	15.7	16.4
23	15.7	14.8

Figure 1. Athens TEC during the 25 April 1979 disturbance.

STATION OSAN
DATE(LOCAL) 90425
GEOM. LAT. +29
SATELLITE ETS2
I.P.P. N35 E128

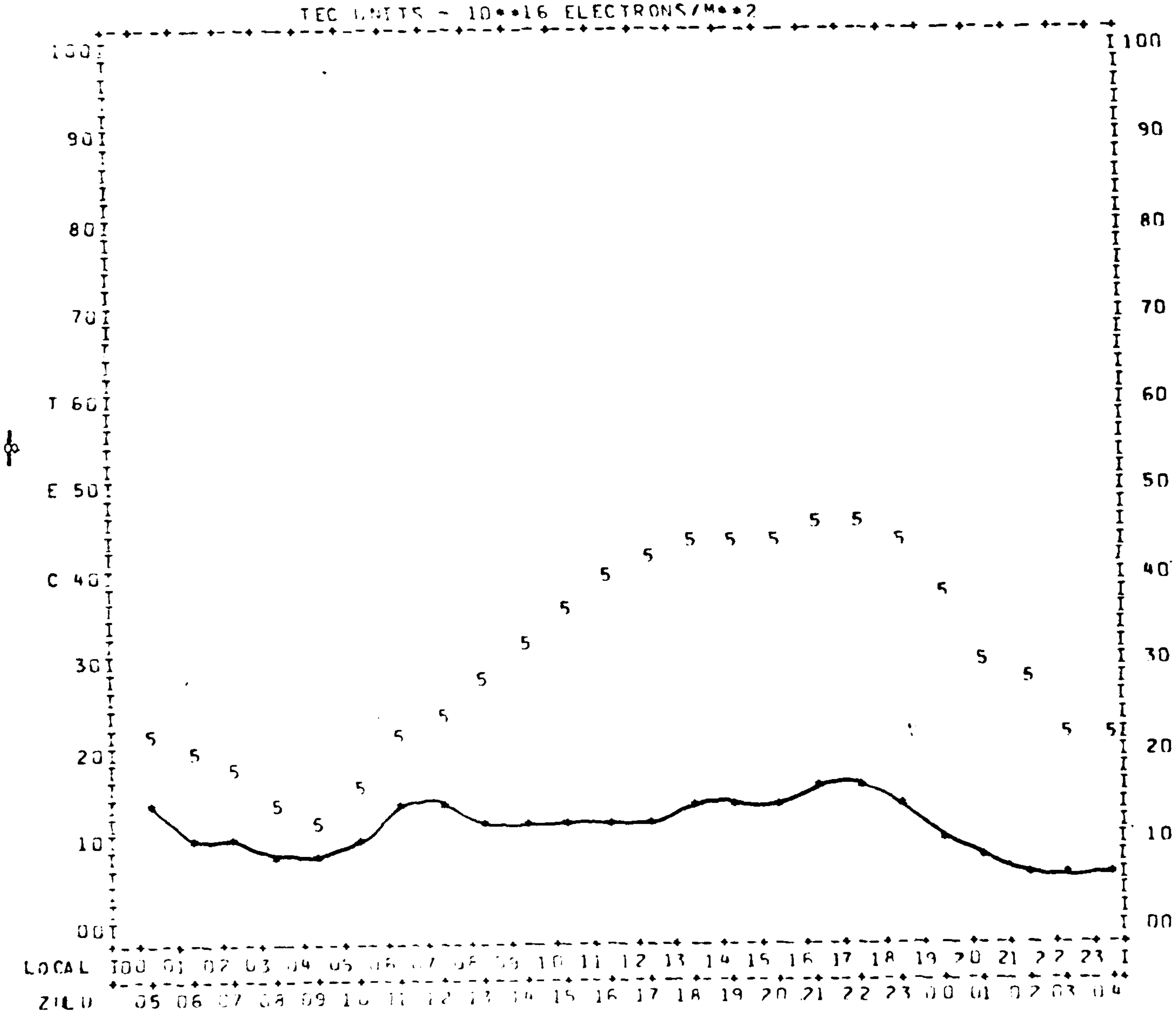


TIME(L)	TEC	MEAN
00	21.8	22.9
01	19.7	19.4
02	16.2	16.5
03	13.4	14.3
04	10.8	11.7
05	9.1	9.1
06	18.5	15.4
07	30.0	27.1
08	33.4	36.4
09	37.9	43.6
10	46.7	49.7
11	64.5	57.7
12	75.1	66.1
13	79.0	71.8
14	96.5	72.4
15	83.5	67.6
16	67.0	61.0
17	68.9	53.1
18	54.5	47.7
19	40.8	42.7
20	38.8	36.1
21	33.7	29.8
22	35.7	25.4
23	32.7	24.3

Figure 2. Osan TEC during the 25 April 1979 disturbance.

STATION SAG HILL
DATE(LOCAL) 90425
GEOM. LAT. +52
SATELLITE ATS5
I.P.P. N39 W 71

5 = five day mean
* = daily TEC value



TIME(L)	TEC	MEAN
00	12.6	20.7
01	10.0	19.4
02	8.6	17.1
03	7.8	14.4
04	7.4	12.4
05	10.1	14.8
06	13.7	20.6
07	14.1	24.3
08	12.4	28.4
09	11.9	32.4
10	11.9	36.4
11	11.9	39.3
12	12.1	41.2
13	12.6	43.7
14	13.9	43.8
15	13.9	43.8
16	15.8	45.2
17	15.7	46.0
18	14.1	44.3
19	10.4	38.2
20	8.0	30.2
21	6.0	26.7
22	5.9	21.3
23	5.4	20.5

Figure 3. Sagamore Hill TEC during the 25 April 1979 disturbance.

```
STATION        PATRICK
DATE(LOCAL)    90425
GEOM. LAT.     +39
SATELLITE      ATS5
I.P.P.         N26  W 80
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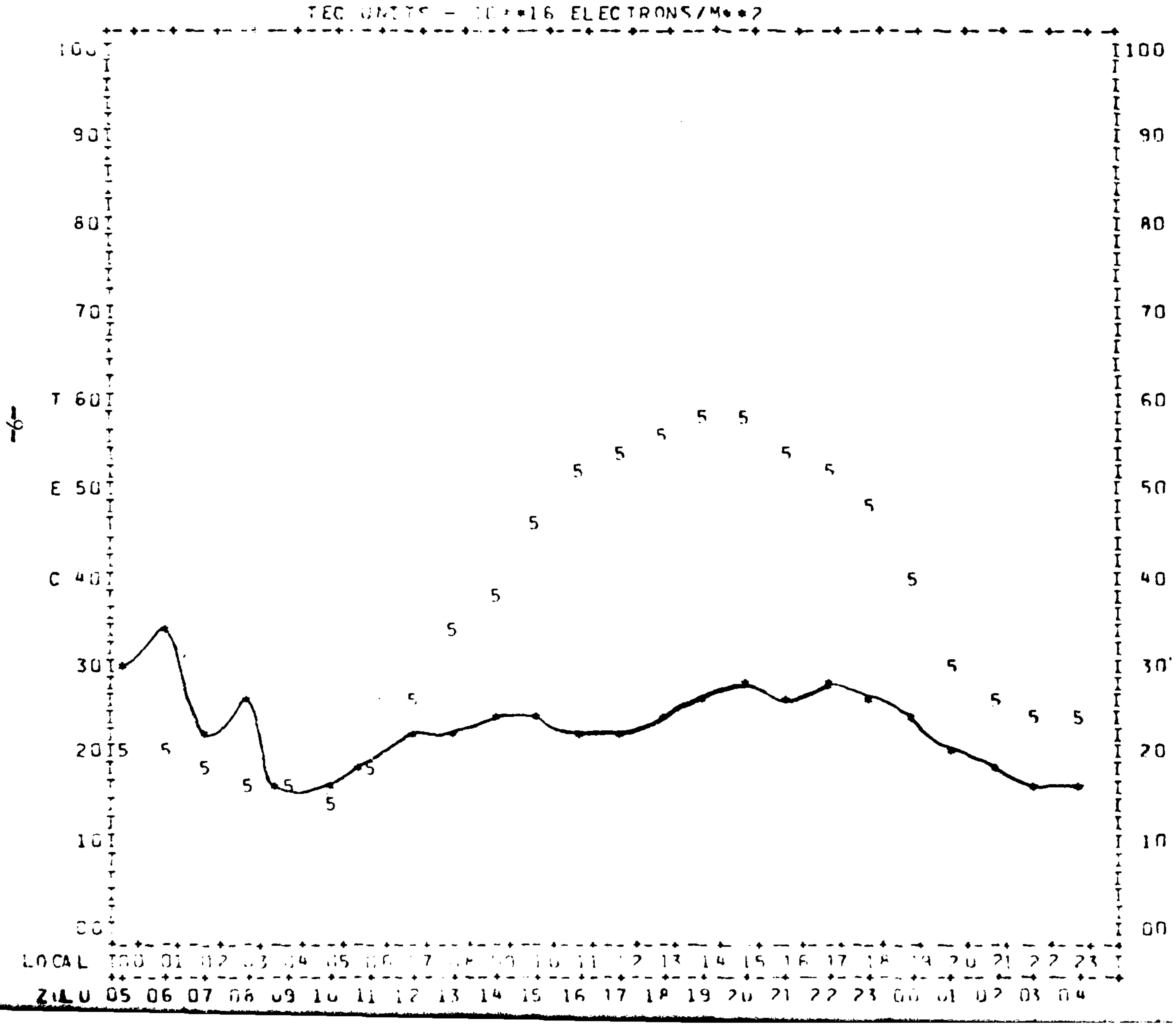
5 = five day mean
* = daily TEC value

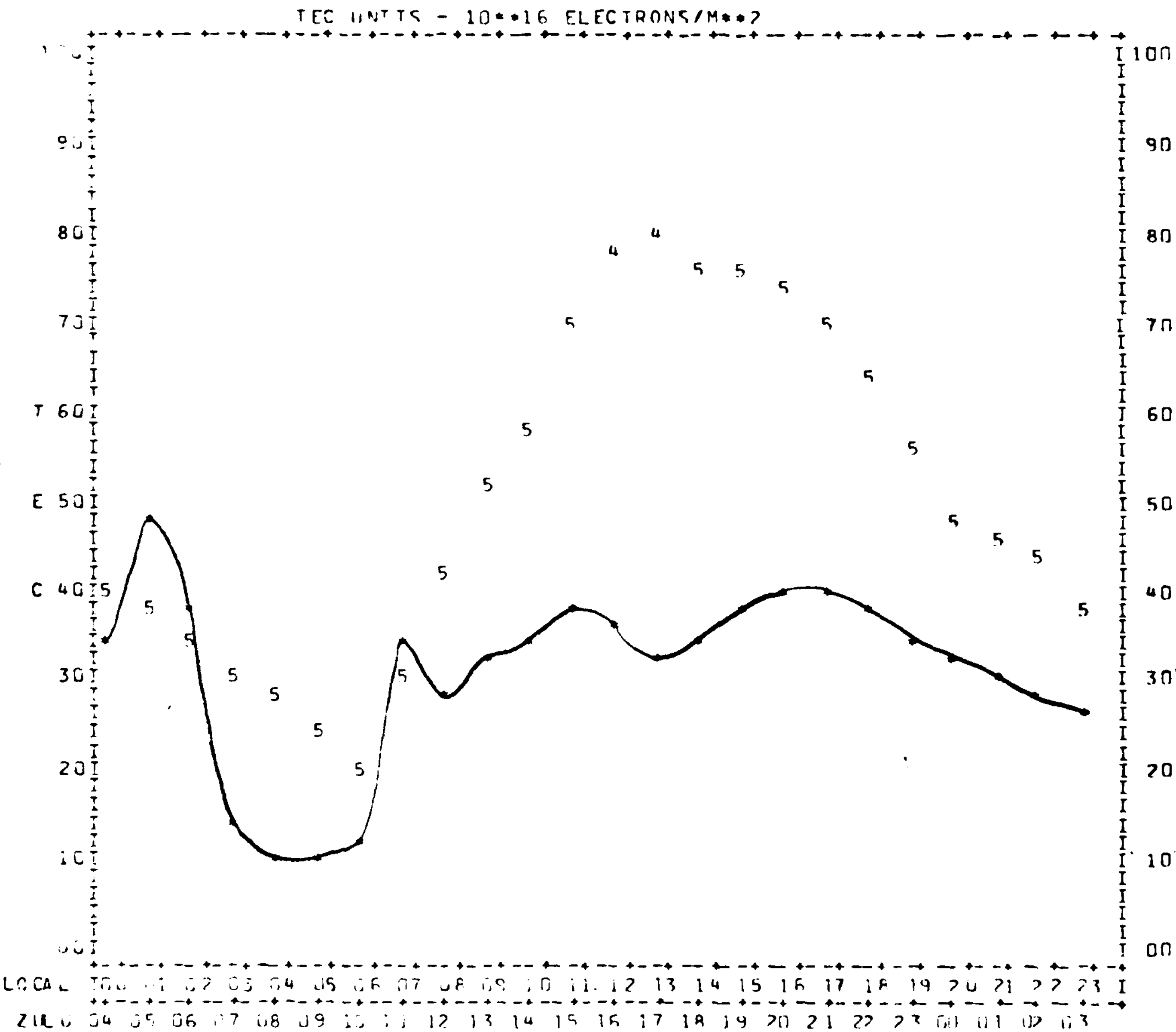


TIME(L)	TEC	MEAN
00	29.8	20.2
01	33.4	19.7
02	22.2	18.2
03	26.1	16.3
04	15.8	14.6
05	15.2	13.1
06	16.8	17.0
07	21.9	26.0
08	21.7	33.5
09	23.8	38.0
10	23.5	45.3
11	22.2	50.7
12	22.4	54.1
13	24.0	56.0
14	26.4	58.3
15	27.7	56.6
16	26.0	54.1
17	27.1	51.0
18	25.0	47.0
19	22.9	39.4
20	19.1	29.2
21	17.0	24.8
22	15.1	24.0
23	15.4	24.0

Figure 4. Patrick TEC during the 25 April 1979 disturbance.

STATION RAMEY AFB
DATE(LOCAL) 90425
GEOM. LAT. +31
SATELLITE ATS5
I.P.P. N17 W 67

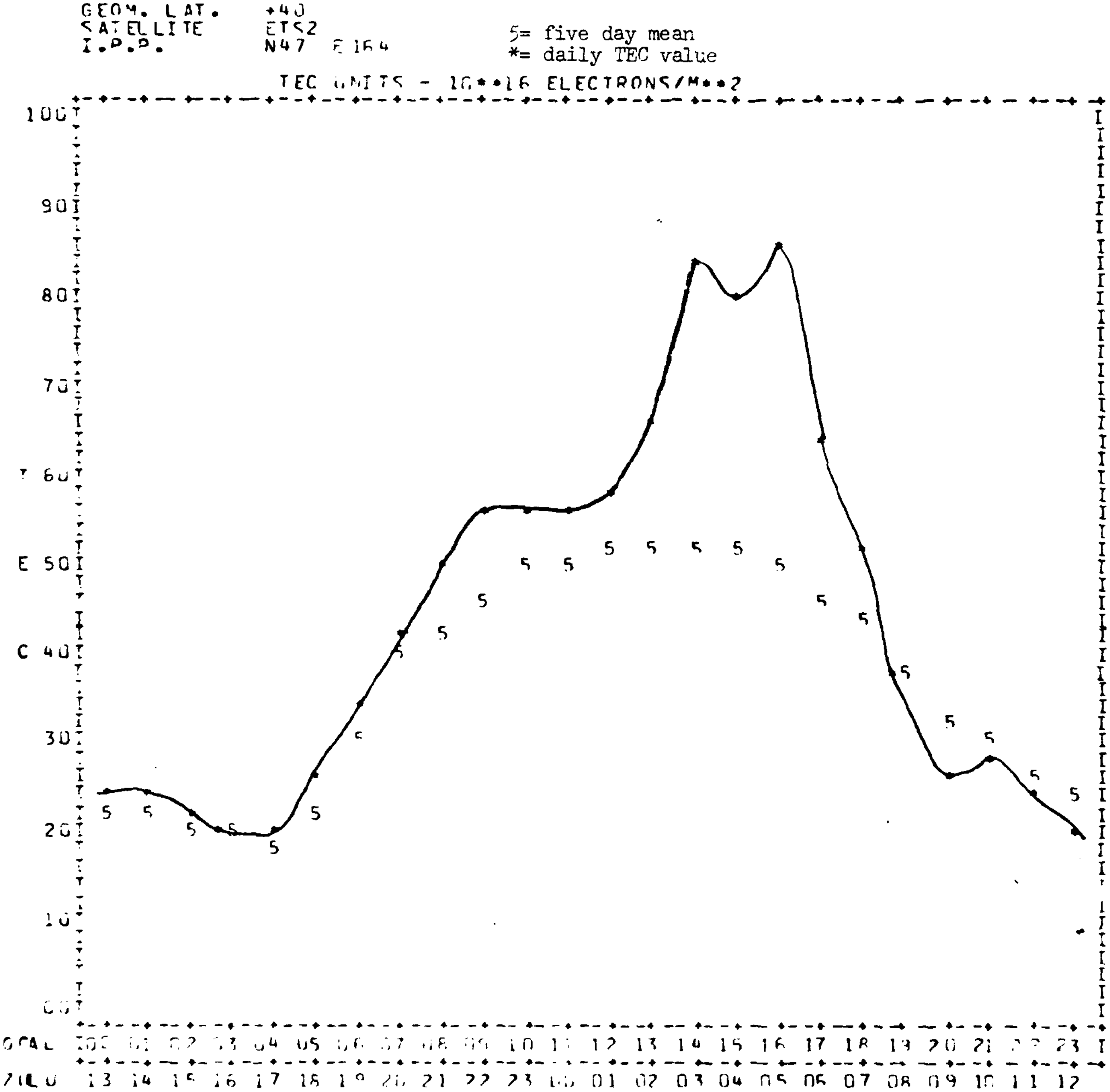
5 = five day mean
* = daily TEC value



TIME(L)	TEC	MEAN
00	32.5	39.6
01	47.8	37.8
02	37.6	34.2
03	13.9	30.3
04	10.3	26.8
05	10.1	27.5
06	12.2	19.2
07	33.5	30.3
08	26.8	47.0
09	31.5	50.8
10	32.7	58.0
11	38.3	68.5
12	35.6	*77.0
13	32.3	*79.1
14	33.8	75.8
15	37.4	75.1
16	39.7	73.6
17	38.7	70.0
18	38.2	63.4
19	34.0	55.4
20	31.8	47.2
21	29.9	45.8
22	27.5	42.8
23	26.4	37.3

Figure 5. Ramey TEC during the 25 April 1979 disturbance.

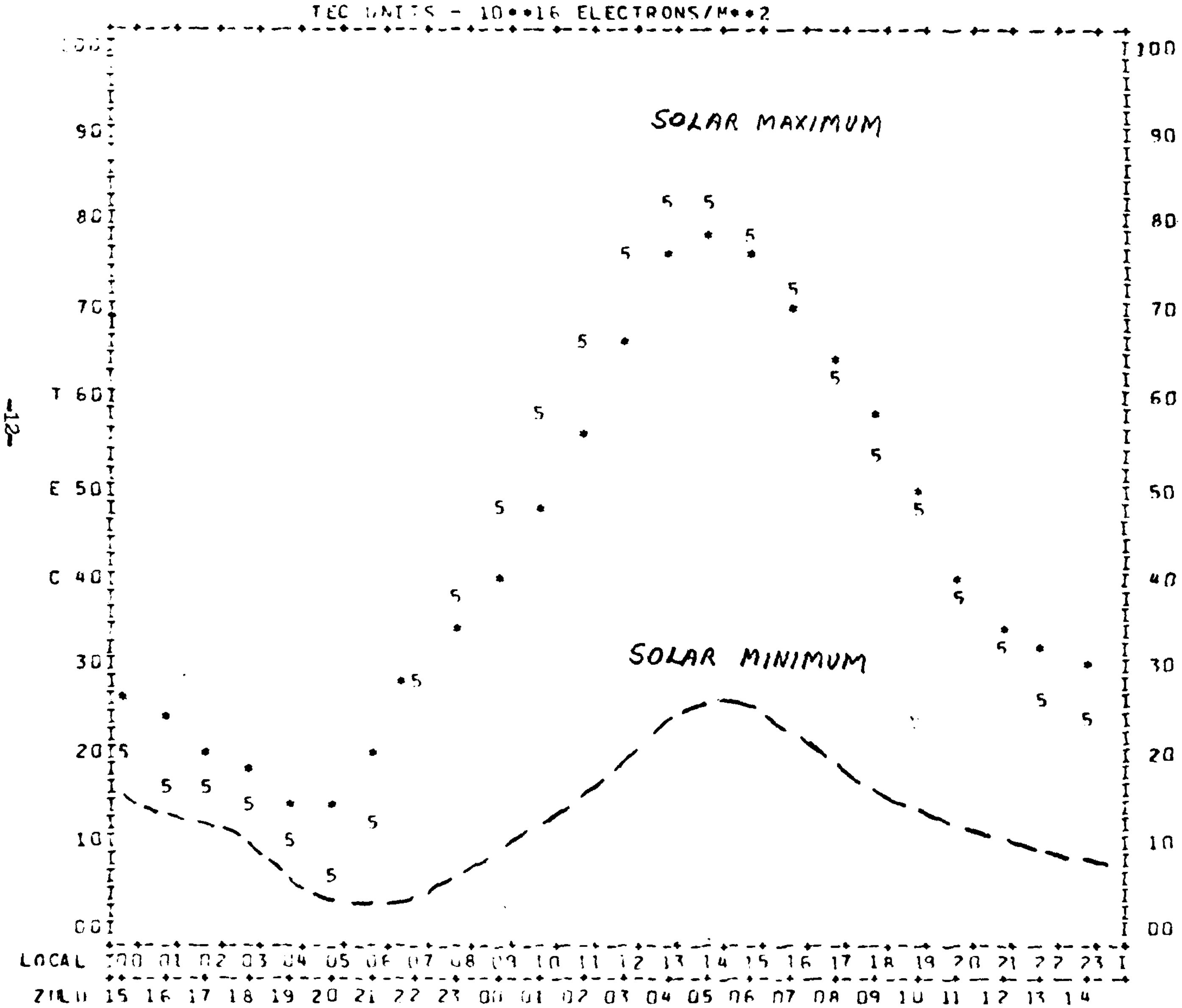
STATION SHEMYA
DATE(LOCAL) 90425
GEOM. LAT. +40
SATELLITE ETS2
I.P.P. N47 E164



TIME(L)	TEC	MEAN
00	22.9	21.3
01	22.5	20.6
02	22.4	20.0
03	20.1	19.0
04	20.4	18.3
05	26.0	21.2
06	33.8	30.4
07	41.3	38.8
08	49.4	42.1
09	55.4	45.7
10	55.3	48.7
11	55.7	50.2
12	58.4	50.8
13	65.9	52.3
14	83.2	52.4
15	79.7	50.5
16	85.0	49.4
17	63.0	46.3
18	50.9	42.7
19	37.5	37.6
20	24.7	32.3
21	27.8	29.5
22	22.9	26.1
23	18.8	23.6

Figure 6. Shemya TEC during the 25 April 1979 disturbance.

STATION	OSAN
DATE(LOCAL)	90420
GEOM. LAT.	+29
SATELLITE	ETS2
I.P.P.	N35 E128



TIME(L)	TEC	MEAN
00	25.3	19.0
01	23.2	15.5
02	20.3	14.5
03	16.6	12.7
04	14.2	9.7
05	13.3	6.3
06	19.8	11.4
07	27.9	26.7
08	34.2	37.9
09	40.7	48.3
10	47.9	58.0
[illegible]	56.4	56.7
12	66.3	74.6
13	76.1	81.1
14	77.6	81.7
15	74.5	78.3
16	68.8	71.3
17	63.8	61.7
18	57.2	53.7
19	48.9	47.1
20	39.7	38.4
21	33.1	30.6
22	30.5	26.0
23	29.4	23.5

Figure 7. The variation in TEC values between solar maximum and solar minimum.

Notable exceptions to those values may occur during disturbed ionospheric conditions or other unusual solar conditions, but the nighttime values do not approach the daytime values.

The large daily variations in TEC during solar maximum also complicate the TEC observing process. The large number of phase changes that have to be determined using the Farady rotation technique adds to the likelihood of erroneous observations. This, in turn, adds an additional workload to the forecaster's effort to have an error-free database.

SUMMARY

TEC forecasting at AFGWC has been limited by a number of difficulties. One of the primary problems is observational data. There are insufficient data for model input or for forecast verification. The existing polarimeter network is hampered by training problems and lack of centralized control. This produces an additional forecaster workload in maintaining a TEC data base. To eliminate this, a future observing network should consist of fully automated, dual frequency TEC measurements.

Because of data problems, the capabilities of AFGWC are essentially untested for area forecasts. Significant advances in the specification model have been made, but its success in an operational environment is unknown because of insufficient observations and/or customer feedback. The solar cycle variations in TEC make it doubtful that the desired accuracies could be achieved during solar maximum. With sufficient observations, the desired prediction accuracies appear achievable during solar minimum. Despite this, daily TEC predictions using the existing data set are a significant improvement over models that are updated only on a monthly basis.

For point forecasts, prediction goals can be met during undisturbed conditions if representative TEC observations are available near the area of interest. However, day to day variations during solar maximum will test the forecaster's skill. Forecaster skill can only be obtained through a thorough knowledge of ionospheric morphology and ionospheric forecasting experience. Because the physical processes are more complex than conventional meteorology and predictive techniques virtually non-existent, forecaster experience in identifying synoptic patterns and trends in the ionosphere is critical to the success of the forecast. TEC forecasting during disturbed conditions shows little or no skill. Observational data problems and forecaster inexperience contribute to this, but inadequate resources have been devoted to this difficult aspect of the forecast problem. Some common features appear at various locations, but their relationship to other geographical parameters is not clear.

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